Image Guidance for All—TilePro Display of 3-Dimensionally Reconstructed Images in Robotic Partial Nephrectomy

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OBJECTIVE To determine the feasibility of a novel low-barrier-to-entry image guidance system.

METHODS Initially a randomized crossover study was performed to establish the interface (iPad or 3-dimensional mouse) that minimized both the amount of time required to perform a manual image registration and the error of that registration. A subsequent clinical feasibility study was undertaken on 5 patients undergoing robot-assisted partial nephrectomy. Randomized crossover study primary outcomes were time to task completion, NASA—Task Load Index score, and alignment error (translational and rotational). The Mann-Whitney *U* test was used to compare groups. Surgeon feedback was sought when assessing the system in a clinical setting.

RESULTS In the initial randomized crossover study, the iPad-based system was able to achieve adequate alignment accuracy (Frobenius norm of 0.3; total error of 20.8 mm) in significantly less time (33 seconds; $P < .01$) than the 3-dimensional mouse interface. The platform received good feedback from the operating surgeon in all instances with the surgeon commenting particularly on the improved appreciation of hilar vascular anatomy.

CONCLUSION In this study, we have demonstrated the feasibility of a "low-barrier-to-entry" image guidance system in a clinical setting. The system was able to achieve swift and sufficiently accurate alignment, with little impact on the surgical workflow. UROLOGY 84: 237–243, 2014.

With the move from open to laparoscopic and finally to robotic surgery, there has been a progressive decrease in the amount of sensory information received by a surgeon performing a given procedure. The greatest casualty of the increasing sensory distance between surgeon and patient is that of haptics.[1,2] The rise of minimal access surgery has been matched by improvements in the way imaging datasets can be processed and displayed. Where traditionally computed tomography (CT) and magnetic resonance imaging (MRI) images were viewed as axial slices on 2-dimensional monitors, they can now be viewed as 3-dimensional (3D) reconstructions with relative ease. This representation of patient anatomy results in an improved ability to localize structures with no increase in cognitive load.[3] A potential solution to the loss of haptic feedback is to augment the surgeon's view with these 3D reconstructions providing him/her with a detailed appreciation of subsurface anatomy, allowing for more informed intraoperative decision making.[4]

Robot-assisted laparoscopic partial nephrectomy (RAPN), using the da Vinci robotic system, is a technique growing in popularity. The steps of vessel identification and tumor resection in partial nephrectomy are often challenging with renal vascular anatomy being highly variable between individuals and renal tumors often being partially or entirely endophytic. It is these characteristics that make partial nephrectomy an ideal index procedure around which a surgical image guidance system is developed.

In this article, we propose and demonstrate the feasibility of a TilePro-based (Intuitive Surgical) image guidance platform for RAPN. The article presents the major steps in the development of the system. Initially, a randomized crossover study was undertaken to establish the interface that minimized both the amount of time required to perform a manual image registration and the error of that registration. A clinical image guidance system was then developed around the best performing interface. The initial clinical experience of the platform is presented herein.

METHODS

Ex Vivo Randomized Crossover Study

Overview. In this randomized crossover study, participants were asked to align prerecorded endoscopic views of a kidney phantom with a 3D reconstruction of the same kidney. The task was

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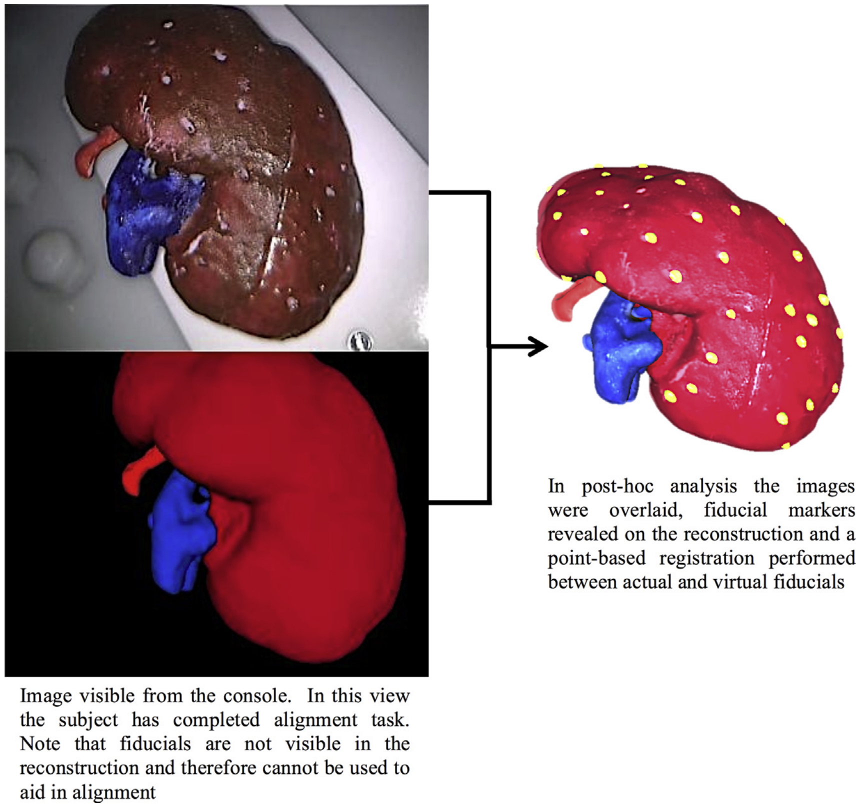

Figure 1. Console view and registration process. (Color version available online.)

performed on a da Vinci Standard (first generation) console using an iPad (Apple) or 3D mouse (SpaceNavigator; 3Dconnexion, Boston) interface. The 3D reconstruction was displayed below the endoscopic view in a fashion akin to the TilePro function of the da Vinci S and Si consoles (Intuitive Surgical, Sunnyvale).

Experimental Design. Initially, a CT scan of a normal kidney was obtained and a segmented reconstruction of the organ was created using ITK-SNAP, version 2.4.0 (www.itksnap.org).[5] From this segmentation, a phantom organ was 3D printed (Objet 260 Connex; Stratasys, MN). The organ phantom was placed in a mannequin orientated in a lateral position, similar to that adopted by patients undergoing RAPN. A series of 3 camera orientations were then recorded.

The study was performed using a dedicated research da Vinci Standard system paired with an iPad or 3D mouse—based image control interface. The rendering of 3D reconstructions was undertaken on a dedicated portable server and fed into the console along with the prerecorded video from the stereoscopic camera (system architecture previously published by Pratt et al[6]), to account for the da Vinci Standard's lack of TilePro. Software was developed allowing an over and under view of the endoscopic feed and 3D reconstruction within the console (Fig. 1).

Fourteen surgical trainees were recruited as participants. Subjects were first given a tutorial in the use of the iPad and 3D mouse interfaces and subsequently allowed 5 minutes to familiarize themselves with respective interfaces. In an attempt to replicate the combination of temporal and accuracy-related pressures in theater, participants were informed that they were being timed but that accuracy of alignment should be their primary concern. Each subject was asked to perform 6 alignment tasks, 3 with each navigation interface (the interface used first was randomized). The tasks consisted of matching the position and orientation of the segmented kidney image with the prerecorded organ phantom orientation (Fig. 1). The same 3 endoscopic views were used for all participants and for both the 3D mouse and iPad. The subject "stopped the clock" when they felt they had performed the best possible alignment.

Outcomes. To establish prior familiarity with the respective interfaces, subjects were asked whether they had ever used a 3D mouse or iPad before.

The cognitive load induced by the respective systems was assessed using the NASA—Task Load Index questionnaire.[7] In addition, participants were asked whether they had a preference for a particular interface, and if so, which one.

Comparing a participant's alignment to a fiducial-based gold standard, with a closed-form point-based registration,[8] allowed an assessment of the accuracy of alignment (registration can be defined as the transformation of one coordinate system to another such that objects are optimally aligned). Five separate outcomes were generated: total fiducial registration error, the error in each individual translational axis (x, y, and z axes), and rotational error.[9] Rotational inaccuracy was represented as a Frobenius norm. This single number represents the magnitude of the incremental rotation required to translate the 3D reconstruction to the orientation of the renal phantom in all rotational axes. Maximal rotational error is represented by a Frobenius norm of 2 whereas perfect alignment corresponds to a value of 0.[9]

Clinical Platform Design

The clinical platform design was based on the results of the initial randomised crossover study. In this study, the iPad-based

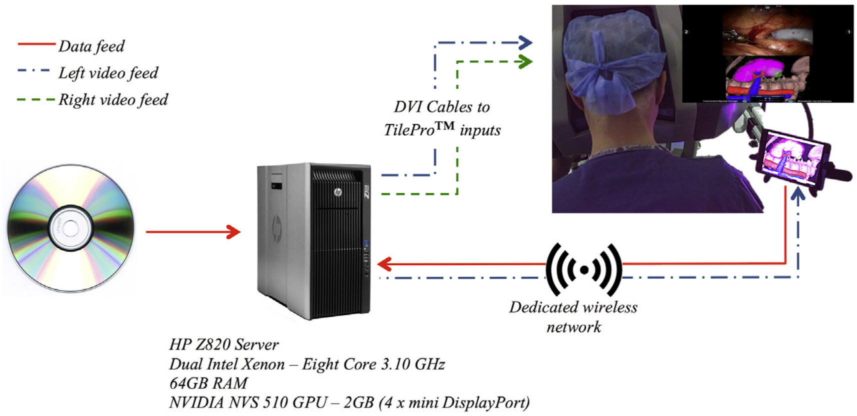

Figure 2. Surgeon inserts CD containing preoperative imaging into an HP Z820 server. The workstation is connected to the da Vinci console via 2 DVI cables (1 for each eye feed). The system uses a wireless iPad interface, with the image visible in the console also visible on the iPad screen (left eye console feed). The surgeon is able to view and manipulate images on the iPad with the reconstructions also visible in stereo in the TilePro function of the console. All image rendering is undertaken on the workstation. (Color version available online.)

interface demonstrated superior subjective and objective performance and as such was the interface chosen for the clinical system. The hardware setup of the platform is detailed in Figure 2. Using preoperative datasets, image reconstructions were performed both volumetrically, using commercially available software (HDVR; Fovia Inc., Palo Alto), and via semi-automated segmentation using ITK-SNAP.[10] Once the segmentations had been performed, the imaging was available to the surgeon in 3 different viewing options: volume rendering, volume rendering combined with segmentations, and 3D polygon meshes derived from the same segmentations (Supplementary Fig. 1).

The clinical platform allowed the surgeon to manipulate the position and orientation of the images, adjust the center of rotation, alter the transfer function of the volumetric rendering (this altering of transfer functions is akin to modifying the window level on a normal 2D grayscale CT), adjust the clipping planes, and save application states (including all of the aforementioned parameters) for subsequent recall.

The planning and image guidance procedure can be divided into the following steps: preoperative planning, anatomic localization, and tumor resection planning (Supplementary Video 1).

Preoperative Planning. During the preoperative planning step, the surgeon was able to view the reconstructed images on his iPad, allowing him to perform mental preprocedural rehearsal. The surgeon was also able to save application states to which he could return during the procedure.

Intraoperative Guidance. During the anatomic localization and tumor resection planning steps, the reconstruction was viewable in 3D within the TilePro function of the console with a copy of the left da Vinci feed viewable on the iPad (Fig. 3). Manipulation of the image on the iPad was replicated within the console view. The surgeon was able to return to presaved application states saved during the preoperative planning step. The system was not used for live guidance of tissue dissection.

Clinical Application

Transperitoneal RAPNs were performed in 5 patients by a single surgeon using a da Vinci Si system. Ethical approval was obtained from the regional ethics committee for the in vivo trial of the image guidance platform (Regional Ethics Committee reference 07/Q0703/24) and written informed consent was obtained from all patients. Patients underwent routine preoperative imaging using magnetic resonance imaging or CT. Preoperative scans were used to create 3D reconstructions of patient anatomy.

Demographics were recorded for all patients and preoperative RENAL nephrometry scores were also calculated.[11] Warm ischemic and total operative times were recorded. Information on postoperative histology, margin status, and complications was collected.

Statistical Analysis

Statistical analysis was performed in GraphPad Prism (GraphPad Software, La Jolla, CA). Medians and interquartile ranges were calculated for all values (data was not normally distributed) and the Mann-Whitney U test of statistical significance applied. A P value <.05 was considered statistically significant.

RESULTS

Randomized Crossover Study

In all, 13 of 14 participants owned an iPad and none had previously used a 3D mouse. When comparing the time to task completion and NASA—Task Load Index scores for the iPad and 3D mouse interfaces, the iPad was found to have significantly shorter alignment times and a lower cognitive load (P <.01 and P <.01, respectively; Table 1). In total, 79% (n = 13) of participants preferred the iPad, 12% (n = 2) the 3D mouse, and 6% (n = 1) expressed no preference.

When assessing the accuracy of the 2 systems, no significant difference was seen in the total registration error achieved by the 2 proposed interfaces (P = .94; Table 1). For the iPad-based platform chosen for use in our clinical system, the greatest error was seen in the z-axis (14.13 mm) with lesser errors of 4.31 mm and 9.97 mm in the x and y-axes, respectively. The median rotational error was represented by a Frobenius norm of 0.29.

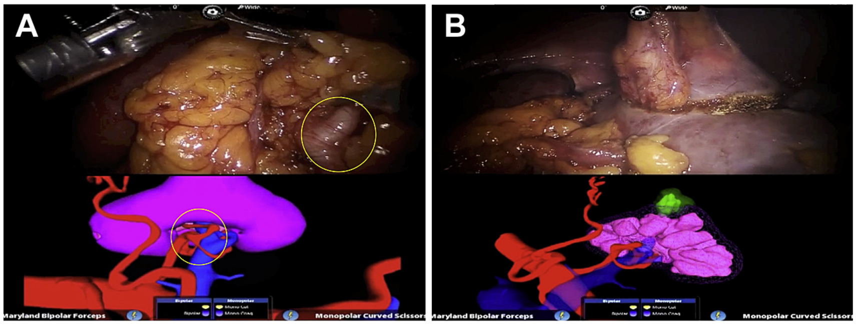

Figure 3. The console view with TilePro enabled. **(A)** The complex hilar vascular anatomy is seen within the image allowing the surgeon to better appreciate the anatomy seen in the operative view. **(B)** The surgeon is able to plan tumor resection by making the surface of the kidney a polygon mesh while keeping the tumor solid. (Color version available online.)

Table 1. Comparison of iPad and 3D mouse interfaces

Variable	3D Mouse, median (IQR)	iPad, median (IQR)	*P* Value
x-Axis error (mm)	4.98 (3.52-7.68)	4.31 (2.44-7.70)	.37
y-Axis error (mm)	8.04 (5.56-10.38)	9.97 (6.63-13.47)	.05
z-Axis error (mm)	15.74 (7.95-21.78)	14.13 (8.56-20.60)	.81
Total error (mm)	20.88 (13.30-26.25)	19.66 (14.21-25.40)	.94
Frobenius norm*	0.25 (0.20-0.41)	0.29 (0.22-0.37)	.67
NASA-TLX score	56 (48.8-63.9)	43.7 (36-50.8)	<.01
Time to task completion (s)	67.5 (42.2-94.8)	40 (24.2-57.5)	<.01

3D, three-dimensional; IQR, interquartile range; NASA-TLX, National Aeronautics and Space Agency Task Load Index.
* Measure of rotational accuracy in all 3 axes, a value of 2 represents the maximum error possible.

Clinical Experience

To date, 5 partial nephrectomies have been performed using the system (Supplementary Table 1). In all cases, the surgeon found the system to be of assistance in the previously outlined steps of preoperative planning, tumor localization, and tumor resection planning. The iPad interface removed the need for a technician in theater to orchestrate the system and perform image registration (a technician was present at all times to troubleshoot any intraoperative issues relating to the platform, at no stage was his assistance required). As and when he required, the surgeon was able to manipulate the images to represent the anatomy visible in the 3D console view to allow him to appreciate better the subsurface structures. When asked whether the imaging had affected the surgical workflow or distracted from the operative view, the operating surgeon did not feel this was the case during any of the 5 procedures. In one of the cases, preoperative imaging revealed complex hilar vascular anatomy with a trifurcating renal artery. The system was felt to be of particular benefit in this case, allowing swift and accurate identification of the trunk of the renal artery through the fat (Fig. 3). Had image guidance not been available for this step, the localization of the renal artery would have been relatively time consuming.

COMMENT

This study has demonstrated both the accuracy and application of a novel image guidance interface. The initial ex vivo study demonstrated that an acceptable level of error could be achieved in a time (33 seconds) short enough to have a minimal effect on the surgical workflow, when using the iPad interface. This alignment was achieved with a level of registration accuracy that the authors believe to be both safe and clinically useful for improving the surgeon's anatomic awareness but insufficiently accurate to provide guidance for image-guided tumor resection (a function for which the platform was not designed). When interpreting the misalignment errors, it is important to consider the effect inaccuracy in each axis will have on a surgeon's appreciation of the anatomy. Perhaps, the most important element of error is rotation, as fairly small errors in rotational alignment will result in a dramatic change in appreciation of anatomic relationships. Rotational error in the alignment tasks performed using both interfaces was small with median Frobenius norms of 0.3 and 0.28 ($P = .57$) for the iPad and 3D mouse, respectively. Alignment in the translational axes is less important as movement along these axes will only affect the location of the organ in the viewing window leaving the organ orientation, and in turn the appreciation of anatomic relationships, unaffected.

In addition to demonstrating the level of registration accuracy, surgeons were able to achieve when aligning a reconstructed organ with a 3D endoscopic scene, this article has demonstrated the utilization of a novel image guidance system in vivo. The platform received good surgeon feedback and gave an improved appreciation of renal hilar and tumor anatomy, allowing intraoperative surgical planning without leaving the console view.

A system using the TilePro function of the da Vinci console has been previously described for both general surgical procedures[12,13] and for partial nephrectomy specifically.[14] In the image guidance system proposed by Lasser et al[14] for partial nephrectomy, preoperative segmented reconstructions (Supplementary Fig. 1) were fed into the Tilepro function of the console. This platform was used for the specific purpose of tumor resection planning with a preoperative virtual resection undertaken to assist in intraoperative planning. The use of preoperative data to actively guide resection is contentious both due to the inability to account for intraoperative tissue deformation[1] and the relatively poor interrater reliability of image segmentation.[15] This said the utilization of preoperative imaging to assist in the appreciation of anatomic relationships, as has been presented here, has the potential to improve surgical efficiency and in turn patient safety.

In their system, Volonté et al used an OsiriX[10] (Pixmeo, Geneva, Switzerland) plug-in that allowed the display of volume rendered images within the console. The translation and rotation of these images could then be altered using the same 3D mouse used in our ex vivo study. Although potentially useful, the system has significant limitations. First, as was demonstrated in our feasibility study, the 3D mouse is associated with a relatively high cognitive load and required a median of 55 seconds to achieve alignment. These factors make a 3D mouse interface unattractive for clinical use.

A further limitation of the previously proposed Osirix-based system[12,13] is the reliance on volume-rendered images alone. Although volume rendering provides visually attractive reconstructions, it struggles to represent internal solid organ and noncontrast enhanced anatomy and is unable to distinguish between surgically relevant and irrelevant anatomy. In RAPN, an example of this shortcoming is volume rendering's inability to represent graphically the normal parenchyma to tumor interface potentially limiting its efficacy in tumor resection planning. In the platform we have proposed, a combination of volume rendered and segmentally reconstructed images (Supplementary Fig. 1) have been used to give the surgeon the best possible appreciation of the anatomy that surrounds their view.

Previous surgical image guidance systems have largely focused on image overlay to provide assistance in determining anatomy.[6,16-21] The fact that the image is being overlaid requires a high level of registration accuracy and achieving this accuracy requires expensive hardware and significant technical expertise in theater. Although valid, this approach provides significant barriers for most surgeons operating outside of large academic institutions. The image guidance system proposed here can be run on an off-the-shelf server and requires no technical expertise in theater mitigating for the issues that have historically confined image guidance to research environments.

In addition to the issues of expense and expertise, concerns have been raised over the safety of image overlay. In a study by Dixon et al[22] examining the effect of image overlay on a surgeon's appreciation of the operative scene, the authors found that surgeons performing a task with overlay engaged were more likely to exhibit inattention blindness. Along with these concerns, the use of image overlay introduces a time lag into the endoscopic video feed, meaning performing tissue dissection under truly live guidance is potentially unsafe. The task of intraoperative guidance in our platform was achieved by displaying the intraoperative video feed alongside the 3D volume rendered and segmented reconstructions thereby addressing both of these issues.

The ex vivo randomized crossover study had a number of limitations. The first of these relates to the simplicity of the alignment task; although representative of the alignment that a surgeon performs intraoperatively, the task was idealized with no perinephric fat or surrounding anatomic structures to confuse the alignment. This may have led to improved accuracy. The second criticism pertains to the respective learning curves for each interface. With only 5 minutes of familiarization and 3 alignment tasks for each orientation, it is likely that the plateau phases of the respective learning curves were not reached, in particular for the 3D mouse interface as the majority (13 of 14) of participants owned an iPad and were therefore familiar with its use. Although this could be viewed as a limitation for an image guidance interface to be accepted by surgeons and adopted into routine clinical practice, it needs to be intuitive enough to be learnt in a short amount of time, and as such, this criticism becomes less relevant.

The clinical system itself is not without limitations. Perhaps, the most obvious of these is that the surgeon is forced to move his gaze between the TilePro and endoscopic views. This introduces the potential for alignment inaccuracies and increased cognitive strain. TilePro also reduces the size of the live operative view, potentially reducing the quality of the surgeon's visual cues; although, this was not reported during our clinical experience.

CONCLUSION

With the loss of haptic feedback in robotic surgery, the operating surgeon has come to rely on visual cues to appreciate the subsurface anatomy. Although the improved visualization in the da Vinci robotic console mitigates, in part, for this loss of haptics, it is unable to replace it. The search for a solution to the loss of haptic feedback has given rise to increasing research efforts in the field of intraoperative image guidance. The systems proposed to date have required access to technical expertise in theater and expensive video capture hardware. The platform presented here requires neither of these. The image guidance system proposed capitalizes on the widely available TilePro function of the robotic console and pairs it with an off-the-shelf computer server, wireless router, and an iPad. This feasibility study has demonstrated the potential for widespread access to image guidance among the

robotic surgical community initially for RAPN and in the future for other robot-assisted procedures.

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Video

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.urology.2014.02.051

EDITORIAL COMMENT

Robotic technology has had a revolutionary impact on minimally invasive uro-oncologic surgery. Cross-sectional imaging provides detailed imagery of the kidney and tumors. As more complex tumors with higher nephrometry scores, such as more endophytic, large and hilar tumors, are being resected, the need for accurate imaging has become even more crucial. This is important given the variable anatomy of the renal hilum and the tumor itself, the proximity of the collecting system, and the body habitus of the patient. It is in this arena that detailed 3-dimensional (3D) imagery and image reconstruction is most appealing. In addition, the TilePro (Intuitive Surgical) feature of the robot allows for importing the relevant images and manipulating them real time during surgery. In essence, it serves as a Global Positioning Navigation System to be used during partial nephrectomy.

The authors report on a novel technology to be used during robotic partial nephrectomy that aims to aid in accurate resection. They introduce a platform using 3D reconstruction imagery with manipulation capability at the time of partial nephrectomy. Using an iPad (Apple) platform is interesting and helpful and the manipulation of the images was facilitated.

Although what the authors describe aids in image quality and interpretation at the time of surgery, the next level to be attained in true image-guided surgery is the concept of virtual reality surgery. More specifically, the 3D detailed images that are generated can be used preoperatively to perform virtual resection of complex tumors using sophisticated imaging software. Additional images are generated preoperatively that would include baseline images of the kidney and tumor and images after virtual preoperative resection is performed. This allows for visualizing the resulting renal remnant and tumor crater to strategize the best approach for tumor resection and reconstruction. The images aid in avoiding injury to crucial arterial branches for hilar and central tumors. Furthermore, the resection can be tailored to prevent exclusion of portions of the collecting system that might occur in complex resections. Both these scenarios can potentially lead to defunctionalized portions of the renal remnant. This concept is currently used in complex tumor resections at our center with encouraging results.[1] We perform preoperative resection of the tumor and import those images also in the surgical field using TilePro, allowing us to assess the resection adequacy and the potential viability of the remnant after surgery. Of course, the most appealing scenario would actually be to also perform renal reconstruction and

parenchymal repair electronically and to overlay all images pertaining to all steps of the operation on the actual surgical image during and after resection. However, because overlay has not yet been possible optimally, this concept that we currently use is as close to virtual reality surgery as possible using the TilePro feature of the robot.

Image-guided surgery and navigation using optimal image quality, virtual reality and image overlay are the future of minimally invasive surgery. As such, studies that explore the horizons of technology that can be used with available state-of-the-art surgical technology belong to the realm of modern clinical urologic surgery and reporting. Hence, the authors have to be commended for their innovative efforts.

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REPLY

We are pleased that our article[1] outlining a novel image guidance system for robot-assisted partial nephrectomy warranted comment and agree with the sentiment that 3-dimensional imaging in combination with the TilePro (Intuitive Surgical) function of the robot can be used as a surgical global positioning system.

It has also been highlighted that image guidance creates the potential for 3D images to assist in preoperative planning.[2] This use of patient-specific virtual reality (VR) offers potential dual benefit. The first, as described, is to allow the surgeon to plan resection preoperatively on preprepared reconstructions, thereby reducing the potential risk to structures such as the collecting system and major arterial branches. Although we agree that this is a worthwhile and feasible exercise, it is important to consider that the current lack of robust tissue deformation modeling methods[3] will reduce the usefulness of this approach. In addition, the process of preparing computerized tomography/magnetic resonance imaging (CT/MRI) imaging for a VR system involves segmented reconstructions; these are subject to significant interrater variability.[4] This further reduces the accuracy of the 3D VR model when compared with the intraoperative anatomy.

The second, and we believe the more exciting potential use for patient-specific VR simulation in the immediate future, lies in preoperative VR rehearsal. This approach would use the console or a simulator, in combination with 3D reconstructions, to facilitate the rehearsal of key procedural steps before the case, within a safe simulated environment. This type of preoperative rehearsal has been shown to improve procedural performance with both patient nonspecific[5] and specific imaging.[6]

The extraordinarily rich datasets obtained preoperatively, through CT and MRI, are currently not maximally used, with surgeons often leaving important information at the door of the operating room. We believe that in the future this information should be available to surgeons before and throughout an operation in a format that is interactive, easy to interpret, and readily available.

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